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Smart Grid Implementation Based on Solar Generation for Load Demand Management in Najaf City, Iraq

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Abstract

Electrical Smart Grids (SG) contain numerous energy and operational measures, including renewable energy resources, energy efficiency resources, smart meters, and appliances. Investigating their applicability in a geographical area is important to provide a firm background to practical considerations. In this paper, the SG model is investigated, considering the available solar generation, hence enhancing residential load demand in Najaf city, Iraq. The analysis begins with an assessment of the electrical load profile characteristics, followed by choosing the optimum orientation of solar panels for the cities, which has been presented using MATLAB software. The optimum tilt angle for each month is estimated for three Photovoltaic (PV) systems of three sizes (1.5kWp, 2kWp, and 2.5 kWp). Furthermore, the study of their generation and impact on load demand is analyzed. The economic and financial analysis has been presented with payback period and benefits. The duck curve generated by the proposed PV systems is discussed. It is found that the annual demand saving of the proposed solar systems is 22%, 31%, and 36%, respectively. The hourly demand saving is presented, and it has been observed that there is overgeneration using 2kWp and 2.5 kWp PV systems, resulting in reshaping the load curve and producing the duck curve. The future work can be summarized by suggesting management of the battery system for the overgeneration.

Keywords: duck curve, solar radiation, SG, PV system, smart grid, electricity, Najaf

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1. Introduction

The growth of the global demand for energy consumption is noticeable in the 21st century because of the increase in population and economic development. 80% of 1.3 billion people around the world live in rural regions where they still lack electricity [1]. Many challenges and obstacles are facing the global electricity sector due to its transition to meet the electricity demand by employing renewable energy sources [2]. Nowadays, the revolution of utilizing renewable energy sources represents the world's recent revolution. Sustainable or renewable energy is defined as the type of source in which its energy is gained from natural sources (regenerate sources) like wind, waves, rain, sunlight, geothermal heat, and tides. Renewable energy has two main advantages: environment-friendly energy resources that do not emit toxic gases causing pollution, and it is renewed naturally over a comparatively short period of time [3]. The report of global renewable energy status from (REN2) declares that the using of fossil fuel sources in the world decreased by (2.3%) from 2011 to 2021, and renewable energy resource usage increased by (3.8 %), as shown in Figure 1. For 2021, the percentage (12.6%) of the total RES consumption is divided into (7.9% solar, wind, geothermal, and biomass), (3.6% hydropower) and (1% biofuels) [4].

Efficient electricity use is critical because it is considered an essential sector of any country. Demand Side Management (DSM) techniques are the practical solution to the mentioned problems, which are represented by load demand shifting, shaving of peak load, the efficiency of the energy, the conservation of the energy, and valley filling. DSM produces the desired changes in the electrical load curve (load curve reshaping) based on monitoring, scheduling, and employment of all designed procedures to affect the consumer's ways of using electricity. There are many benefits of DSM, including the enhancement of the distribution network and transmission grid and the

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efficiency of operation. The second benefit is reducing the generation margin. There are various definitions of DSM for different categories of people. This means that utility companies are delaying and avoiding the necessity of constructing new electric power plants by shifting and reducing the user's period of energy consumption. DSM means - for domestic consumers - a strategy for saving money by reducing the electricity bill. For industrial customers, it means lowering the price of production and then producing the best product in the market. I.e., the term DSM points out to scenarios handled by utility and consumer for adjustment of the time and amount of the consumption of electrical energy to make the preferred reshaping of electrical load profile [5].

In order to improve the dependability, effectiveness, and safety of the electric power system, the SG was developed utilizing communication, computers, sensors, and automation for an updated power grid. SG gives the consumer the ability to control and manage the usage of electricity, and hence, it lowers electricity rates effectively and efficiently by reducing energy consumption [6]. It works based on the concept of bidirectional flow between the information and electricity, making an automated delivery process. The primary purposes of the SG are improving DSM and energy efficiency, as well as supporting reliable grid protection. With high accuracy of operation, SG provides real-time controlling, monitoring, and balancing based on the integration of several two-way (bidirectional) smart devices (such as meters, actuators, and sensors) [7]. Photovoltaic generators that convert solar radiation into electricity have many considerable advantages, such as being environmentally friendly, silent, inexhaustible, fuel-free, and having a long lifetime. The output period of PV power systems partially coincides with the peak electricity load demand throughout the day, and as a result, the application of demand-side management based on solar energy systems has attracted attention recently [8]. The combination of management concepts and PV systems produces a SG.

The major issue Iraq faces is the shortage of generated electricity. Iraq's over-reliance on burning fossil fuels to generate electricity has led to several environmental challenges and placed heavy burdens on the Ministry of Oil to cover the demand growth for electricity. By this means, natural gas is supplied to power plants in order to maintain levels of electricity production, which cannot be sustained due to the absence of foreign direct investment in the country's gas reserves.

Because of the good geographical location of Iraq, the global daily solar radiation amount incident on a flat panel is expected from (5) to (5.5) kWh/m² per day (see Figure 2) [9]. Ambitiously, Iraq had planned to develop solar power in the 1980s. The first rooftop solar panels in the Middle East were installed at the Research Center of Solar Energy in Baghdad in 1986 after approving the renewable energy law in 1982. However, three decades of war and economic challenges have severely weakened the plans and proposed projects for the country’s renewable energy implementation. Progress in this area stalled until 2009 when the Ministry of Electricity announced a plan to light the streets of Baghdad by installing 6,000 solar-powered lamps. The project failed due to a lack of regular maintenance, high weather temperatures, and the solar lighting system was not installed properly [10]. Unfortunately, Iraq does not have a renewable energy policy or a clear strategy to be dependent over the next decade for utilizing solar energy. The lack of basic and straightforward legislation for investment in solar energy resources restricts the development and widespread adoption of renewable energy due to several reasons: high subsidies for traditional energy sources, the absence of regulatory frameworks for electricity trading, limited financing for long-term projects, the lack of support for investors from international banks and financing institutions and high initial investment costs.

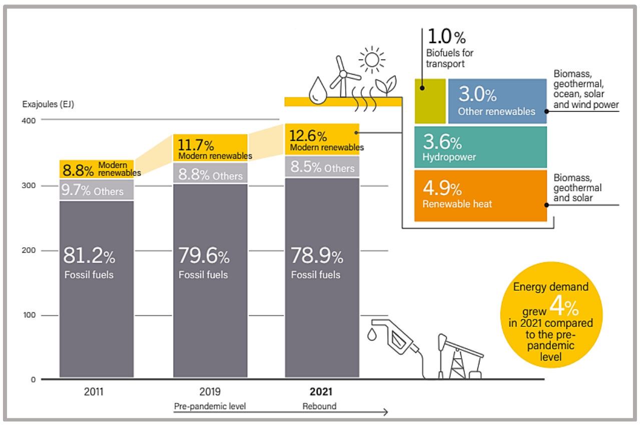

Figure 1. Total energy consumption by sources (2011-2021) [4].

Therefore, numerous studies have been suggested on the application of solar energy technology in Iraq. Afaneen A. Abbood et al. presented a design of a solar energy system for each customer in a scale of households for Baghdad city, Iraq. Hence, the management of electricity peak load was thoroughly explained [11]. Hasan N. Muslim suggested a general program to optimize the solar tilt angle using the software MATLAB. This algorithm is proposed to maximize the solar generation for different case studies: New Delhi, California, and Najaf city. Based on their optimal tilt angles for each month, solar radiation is calculated. This proposed algorithm is common flowchart software and can be useful for most locations on the earth by varying the related data of the chosen region (longitude and latitude) [12]. Salwan S. Dihrab and K. Sopian demonstrated the design of a (PV/Wind) renewable energy system of electric power generation (hybrid system) for the grid-connected system in Iraq for three different cities using MATLAB simulation [13]. Afaneen A. Abbood et al. suggested the design of a 1MW PV system grid connected type for Karbala city under Iraq climate conditions using MATLAB [14]. Shaima M. D. Al-Janabi and Fadhel A. Jumaa demonstrated a study for the design and installation of a rooftop solar PV system based on the electrical load requirements of houses located in Diyala city, Iraq. He depends on PVsyst software for examination and simulation of the performance ratio for the proposed system with losses [15]. Amina M. Shakir et al. suggested a PV bifacial module energy system with a size of 100 kW for a grid-connected PV system in three cities in Iraq (Baghdad, Mosul, and Basrah) using the PVsyst program [16]. A.L. Mahmood presented a stand-alone PV power system to supply department laboratories at Al-Nahrain University in Baghdad city to ensure power continuity [17].

In the Middle East region, various studies have been presented to highlight the application of DSM and solar PV in the SG. Hussam J. Khasawneh et al. proposed an approach for optimized utilization of solar energy in residential sector of Jordan. The introduced algorithm is applied to 5kWp solar PV system based on machine learning scenarios for solar power management analysis. The research presented the application of load shifting Technique with decreasing the dependency on grid with more than 26% [18]. Elfatah, Atef A et al. introduced optimization for sizing standalone hybrid PV/diesel generators/battery storage system for delivering electrical loads in Luxor, Egypt. The optimization was done based on flow direction algorithm [19]. Ramin Torkan et al. demonstrated optimization for management and planning in micro-grid (MG), with participation of costumers for implementation the demand response scenarios, in order to reduce the cost of operation and reduction loads. The applied method for technical and economic issues in the MG was genetic algorithm [20].

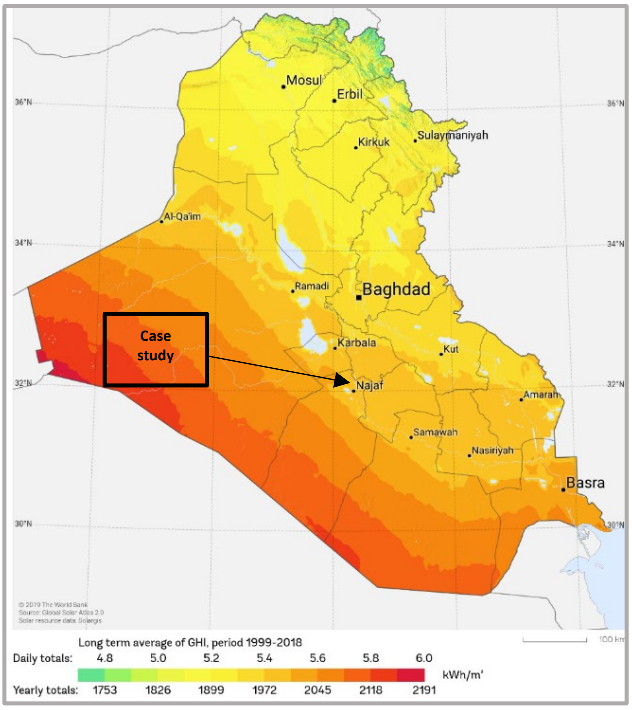

Figure 2. Global solar radiation on horizontal surface in Iraq based on solar map of GIS [9].

2. Research Methodology

In this study, the SG concept is applied based on the solar PV system design. The load curve analysis has been presented in this work for Najaf city. Then, the solar tilt angle optimization to get the maximum solar generation is analysed based on MATLAB software. After that, three PV systems are proposed to cover the load demand in the residential sector in Najaf city, followed by a study of the impact of solar PV generation of the suggested solar systems. The structure of this paper will be discussed in the following sections.

The methodology of the research can be summarized as follows;

1. Analysis of the load profile curve and study of the peak periods using MATLAB. This point is important for choosing the optimal design of the PV system.
2. Solar tilt angle optimization is based on MATLAB software in order to maximize solar generation.
3. Calculation of the solar PV generation for different system sizes.
4. Studying the effect of high PV penetration on the load profile curve.
5. Studying the economic analysis of the proposed PV system.

3. Load Profile Characteristics

The electrical load profile or electrical load curve describes the variation of the consumption of electricity demand with time, and it differs from one region to another. As a result, the load profile depends on many parameters, such as the weather conditions, the time of power consumption in a day, the price of electricity, the type of season, and the category of activity [21]. In this section, the analysis of the electrical load profile of Najaf city will be presented as the first step in this work. The analysed data was unpublished and it is from Ministry of electricity in Iraq. To be more beneficial, the design of the PV system essentially depends on the following factors;

1. The characteristics of the electricity consumption in which helps us to predict the variation of load profile and study the pattern of load demand to be covered by the solar system.

2. The size of solar PV system in the sites to be installed, i.e., the electricity generation of PV systems in the locations where the solar cells are installed.

3. The solar system can be connected to the grid through either an on-grid or stand-alone PV system.

4. The metrological and environmental parameters and the intensity of solar irradiation in the sites where solar panels are to be installed.

5. The economic feasibility of the proposed PV project and the study of achieving the expected profits or whether it will cover its expenses.

The Najaf city lies in the Middle Euphrates of Iraq (Middle Euphrates is a geographical region located in the upper south of Iraq, in the middle section of the Euphrates

River inside Iraq). This city is considered one of the hot cities, as it is characterized by a noticeable rise in temperatures during the summer season. Based on the data from the Ministry of Electricity in Iraq, the load profile in Najaf city has two peak periods, one in the daytime and the other in the night time. Hence, the load demand is increased as an overall percentage. Figure 3 shows the noticeable expansion in the load demand for this city during (2010-2022), as well as the expansion in power generation.

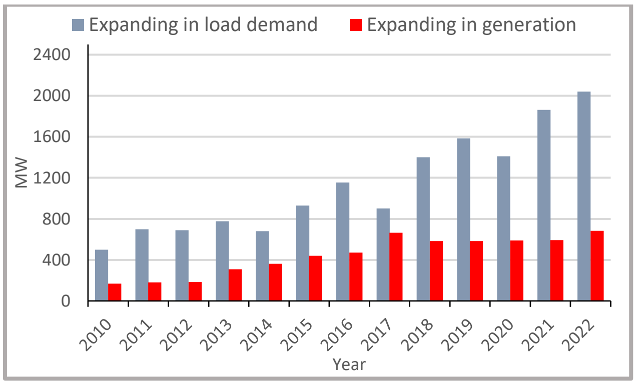

Figure 3. Load demand and power generation for Najaf city (2010-2022).

The load curve is defined as the change in demand or consumption of electrical energy by consumers during 24 hours. It consists of three regions: base load is the load that is constant throughout the year. The types of power stations to cover this type of load are nuclear stations, thermal stations, gas stations, and coal stations; where it is preferable to cover this area with the cheapest and most durable sources without stopping during the year, and it represents the first 25% of the load duration curve. The second type of load is intermediate load, which changes seasonally, and gas stations cover this area mainly, as these stations can be turned off seasonally according to their necessity. The third region of the load curve is peak load, in which required capacity changes hourly during the day. The power stations that cover this area can operate daily and be turned off during the day, and sometimes, they resort to means of storing electrical energy. The average load profile for each month of the year 2014 is shown in Figure 4. The load patterns are represented by the averages for each residential consumer in Najaf city. It is obvious that the maximum consumed energy is 2449 W in August at 9 PM, followed by July with peak demand at 9 PM at 2300 W.

For more analysis of load demand data, the load duration curve can be seen in Figure 5. It can be observed that the last 25% of the load duration curve represents the peak load. The number of peak hours during 2014 for Najaf city is (2239) with a percentage of 26% of the year. This percentage is acceptable restively and can be reprocessed and analysed to be covered. The range of peak power (530-650) MW.

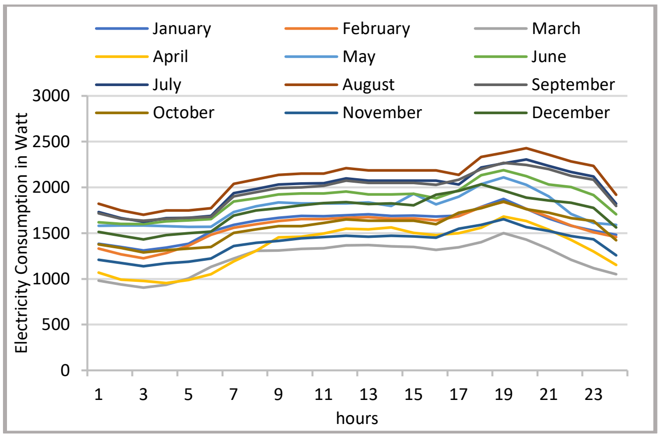

Figure 4. Average load profile for each residential user of each month during 2014.

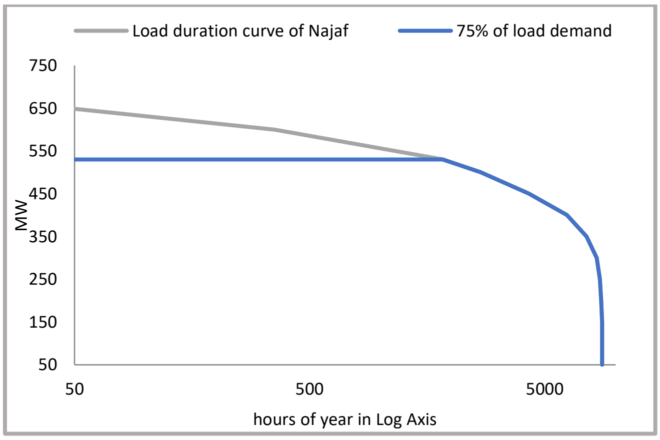

Figure 5. Load duration curve for 2014 in Najaf city.

The load demand of Najaf city differs from one season to another. To study the behaviour of load patterns, the analysis for a week in winter and summer has been presented, as shown in Figure 6. The load demand in summer is chosen for days (6-July-2014) to (12-July-2014). It is noted that there are repeated load curves with the same consumption values. In the middle of the week, there is a reduction in electricity usage. Also, the load demand for the winter is chosen for days (5-January-2014) to (11-January-2014). There is a decrease in electricity consumption over the weekend. Also, the peak load period is only at night, with a noticeable reduction in load at the last hours of the night. This curve represents the consumed power in all sectors (residential, commercial, agricultural, and governmental).

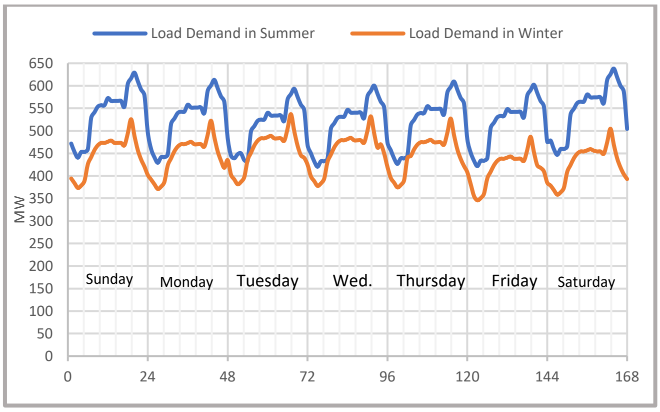

Figure 6. load demand for a week in winter and summer.

4. Theoretical Background of Estimation the Solar Radiation and PV Generation

The density of the solar radiation power is called Insolation. However, the solar constant definition is the solar radiation outside the earth's atmosphere, which faces the sun, and its value is about 1360 W/m2. In addition, the solar constant is the value of solar radiation that faces the vertical sun for any surface (at sea level) with clear sky conditions, and its rate is approximately 1 kW/m2. So, the solar Insolation depends on [22, 12]:

1. The transparency level of the atmosphere.
2. The surface orientation with respect to the sun.

Also, the main errors that may happen in calculations of the solar radiations are:

1. The equation of time is applied to correct the supposition throughout the year, while the period between sequential sunrises stays constant, which is inaccurate.
2. The difference between the applied mean local time and civil time in different equations (the measured time at the centre for each time zone).
3. Reducing the accuracy by considering the geometry of the situation in the formulas. Due to the diffraction of the light, this error occurs as a result of the presence of the atmosphere. So, the geometric sunrise will be after the apparent one, and the apparent sunset will be later. To overcome this error, instead of the geometric solar zenith angle sunset and sunrise 90, it should be corrected into 90.833.
4. The clear atmosphere assumption during the collection of solar radiation data is inexact, as the amount of useful sunlight depends on the meteorological conditions.

Solar radiation is the beam of radiation created by the sun, and its unit of measurement is W/m^2 with a wavelength of (0.3 µm-2.5 µm) and 1000 W/m^2 can be considered as the maximum amount of solar radiation that reaches the earth's surface. The first step in this work is the calculations of solar radiation based on the optimization of solar tilt angle for Najaf city.

The hourly solar radiation for a tilted surface can be estimated from the following equation [12, 22, 23]:

$$R_T = R_H \times \frac{cos\theta}{cos\theta_z} \quad (1)$$

Where;
R_T: Solar radiation on a tilted surface (W/m^2).
R_H: Solar radiation on a horizontal surface (W/m^2), which can be calculated from the equation;

$$R_h = R_{sc}\left[1 + 0.033\ cos\frac{2\pi J}{365}\right] cos\theta_z \times 0.7^{\left(\frac{1}{cos\theta_z}\right)^{0.678}} \quad (2)$$

$$cos\theta_z = (cos\emptyset\ cos\delta\ cos\omega + sin\emptyset\ sin\delta) \quad (3)$$

$$\begin{aligned} cos\theta = {} & sin\delta\ sin\emptyset\ cos\beta - sin\delta\ cos\emptyset\ sin\beta\ cos\gamma \\ & + cos\delta\ cos\emptyset\ cos\beta\ cos\omega \\ & + cos\delta\ sin\emptyset\ sin\beta\ cos\gamma\ cos\omega \\ & + cos\delta\ sin\beta\ sin\gamma\ sin\omega \end{aligned} \quad (4)$$

Where;
R_{SC}: Solar constant.
θ_z: Zenith angle.
$\emptyset$: Geographical latitude or the case study.
β: Tilt angle.
γ: Azimuth angle.
δ: Solar declination angle, can be estimated from the below equation;

$$\delta = 23.5 \sin\left[\frac{360}{365}(J + 284)\right]. \quad J\ is\ day\ number \quad (5)$$

ω: Hour angle, can be calculated from below equation.

$$\omega = 15(12 - ST). \quad where\ ST\ is\ solar\ time \quad (6)$$

$$ST = LT + \frac{ET}{60} + \frac{4}{60}(L_s - L_L) \quad (7)$$

ET: Equation o time, can be calculated by;

$$ET = 9.87\ sin2f - 7.53\ cosf - 1.5\ sinf \quad (8)$$

LT: Local time (1-24).
L_S: Standard meridian of local time.
L_L: Geographical longitude.

$$f = (360\ (J - 81))/365 \quad (9)$$

The functionality, composition, and classification of solar PV systems are determined based on the operational requirements and the connection of the equipment of PV systems to the electrical loads and other power sources. PV systems can be classified into connected systems and standalone systems. For backup power purposes, renewable energy systems are considered hybrid systems if a wind generator or diesel engine generator is used as a backup source. These renewable systems, especially PV systems, are independent renewable energy systems. However, the batteries are not usually included in the straight connection of the PV system. Therefore, solar power systems without batteries operate only during sunlight hours in the daytime, which makes them appropriate for common applications such as fans, small pumps, water pumps, and solar water heating systems. To take advantage of PV systems, in which the maximum power output is produced, they use a DC-DC converter or a maximum power point tracker (MPPT). To make these systems output power more stable and safer, most PV systems use batteries to store the surplus generated energy [22, 23].

The DC power output of the PV systems depends on numerous factors that can be summarized as follows:

1. The efficiency of the solar cells used in the system: This means that it can only be used for the value of the efficiency from the incident radiation on cells. So, if we have a radiation of (1000 W/m^2) with cell efficiency (20%), this indicates that we will use only (200 W) in one-meter square.
2. The area benefiting from installing solar cells.
3. The incident solar radiation in the area where the solar systems are being installed.
4. The module operating temperature also affected the performance of solar cells.
5. The material the solar cells are made of.
6. Other factors may influence the PV production are the dust, shadow…etc.

The main equation to evaluate the solar generation ($P_{PV-Output}$) is as follows [24, 25, 26]:

$$P_{PV-Output} = \eta_{ref.}[1 - \beta(T_{amb.} + k \cdot R - T_{ref.})] \times R \times A \quad (10)$$

Where,

$\eta_{ref.}$: is the efficiency of solar panel at reference temperature (25 °C). This efficiency given in the datasheet of the installed module.

β: is the temperature coefficient of the cell material at standard test conditions. This parameter given in the datasheet of solar cell.

$T_{amb.}$: is the ambient temperature.

k: is the thermal coefficient, and typically chosen (0.02).

R: is the solar radiation on a tilted surface.

$T_{ref.}$: is the reference or standard temperature (25 °C).

A: is the area that the solar cell to be installed.

5. Input Data and Assumptions

In this work, the input data for estimation the solar radiation and solar generation are:

1. Azimuth angle (γ) is zero because the orientation of solar panels into south.
2. Solar constant (R_{SC}) is 1.367 kJ/m^2.
3. Day number (J) from 1 to 365.
4. The local time (LT) from 1 to 24.
5. Geographical latitude ($\emptyset$) for Najaf city is 32.0259°.
6. Geographical longitude (L_L) is 44.3462°.
7. Standard meridian of local time (L_S) is 45°.

It is important to note that some limitations and assumptions underlying this work. First, the solar generation analysis relies on theoretical or average irradiance and climate data, which may not accurately reflect daily or seasonal variations in weather conditions such as heavy cloud cover or dust storms experienced in Najaf. Second, simplified models were used to represent the load and generation characteristics, including the assumption of stable solar panel performance and the failure to account for gradual degradation or long-term efficiency loss. Furthermore, the effects of partial shading or variations in roof angles were not considered in detail, but rather a general ideal slope angle was used.

Furthermore, the research assumes that the grid infrastructure is capable of accommodating integration with distributed generation systems without significant technical obstacles, while the practical reality may require upgrades to protection systems or grid management. These assumptions and limitations represent points that can be developed in the future by adopting more detailed climate data, long-term field experiments, and a deeper study of grid integration.

6. Tilt Angle Optimization and Solar PV Generation

The previous equations explained in section 4 are deployed in simulation on MATLAB software and the flowchart of the proposed algorithm is illustrated in Figure 8. The optimal tilt angle for each month in Najaf city based on the proposed algorithm can be noted in Figure 7. Then, the obtained solar radiation is based on the optimal tilt angle for each month, as shown in Figure 9. It is assumed that the panels are oriented towards the south, which means that the azimuth angle equals zero.

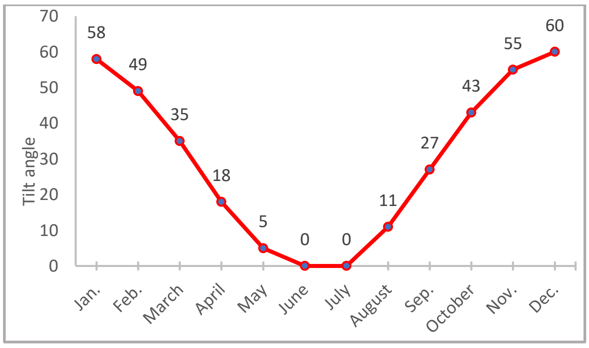

Figure 7. Optimum solar tilt angle in Najaf city [12].

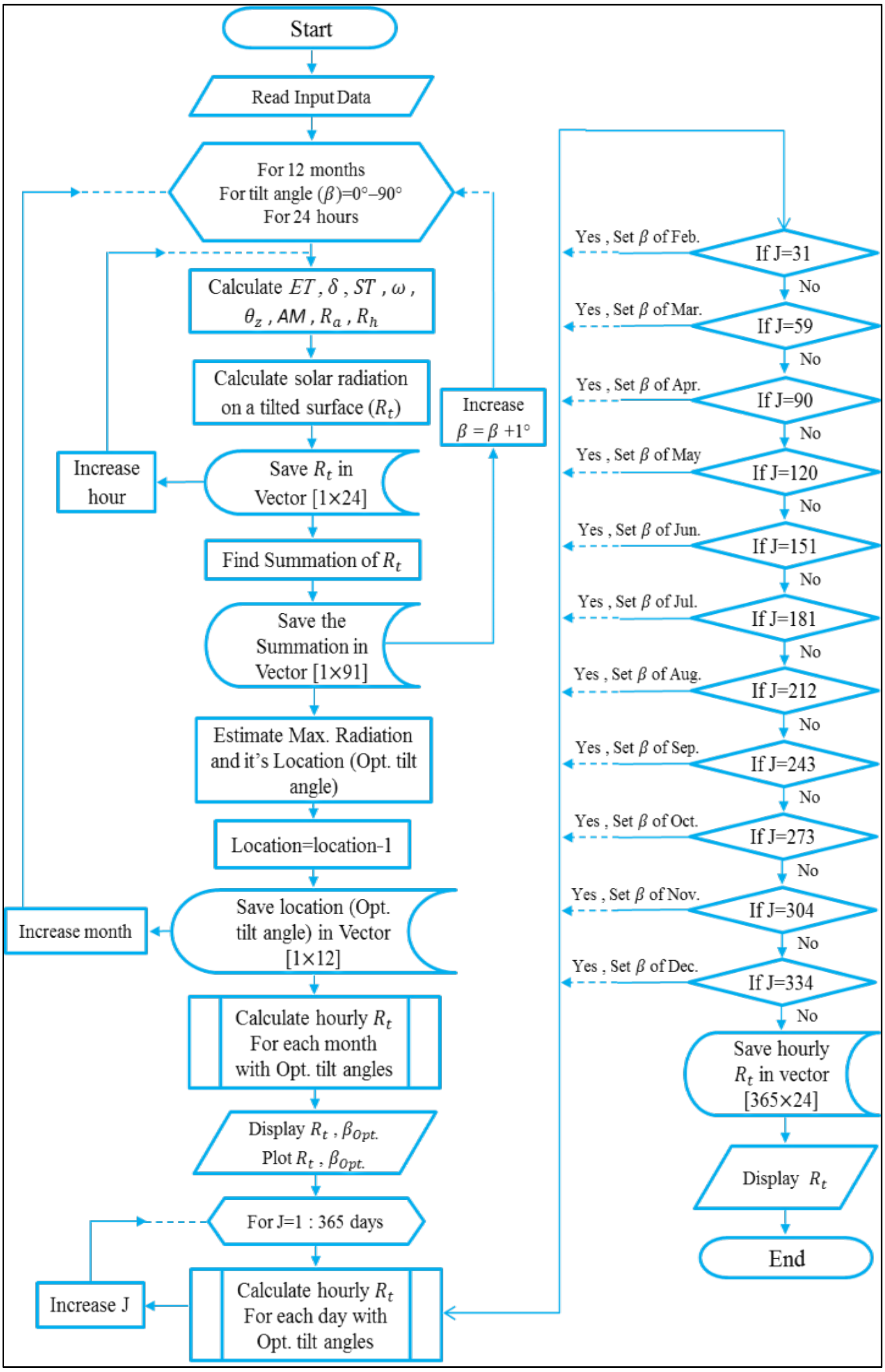

Figure 8. solar radiation estimation based on optimum tilt angle [12].

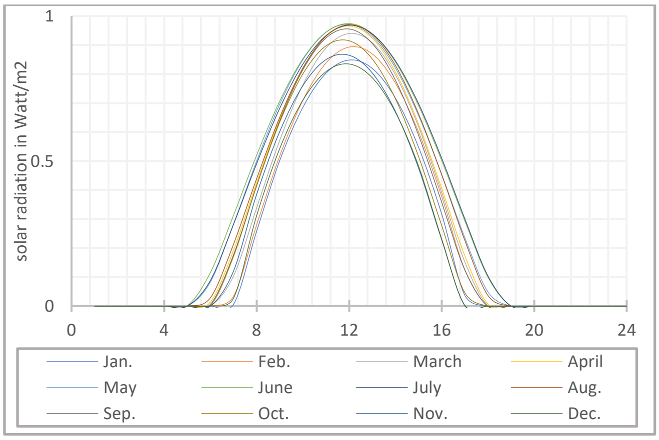

Figure 9. Solar radiation for each month in Najaf city with optimally tilt angle [12].

In this work, the specifications of the proposed solar system can be illustrated in Table (1). The average daily consumption for each consumer vary between (1.2-2) kW based on the analyzed data in section 3. Therefore, the suggested PV systems that meet the load demand for each residential consumer are three sizes: 1.5 kWp, 2 kWp, and 2.5 kWp. The comparison in demand savings for each size will be presented in the next section. The power generation from 1.5 kWp PV system can be seen in Figure 10. The solar generation for 2 kWp and 2.5 kWp systems are shown in Figure 11 and Figure 12, respectively.

Table 1. PV system parameters and specifications for different proposed sizes.

System size = 1.5 kWp		System size = 2 kWp		System size = 2.5 kWp	
No. of panels	5	No. of panels	7	No. of panels	8
System area	8 m^2	System area	11 m^2	System area	13 m^2
Nominal panel Power			320 W		
Panel efficiency			19.8 %		
Panel area			1.6 m^2		
Rated voltage			54.7 V		
Rated current			5.86 A		
Max. series fuse			20 A		
Temp. coefficient			-0.38 %/°C		

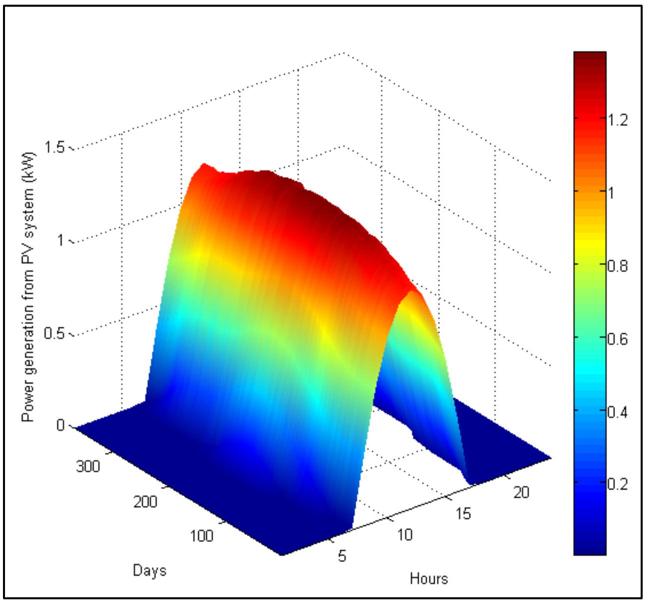

Figure 10. Solar generation for each day in Najaf city with optimally tilt angle for system 1.5kWp.

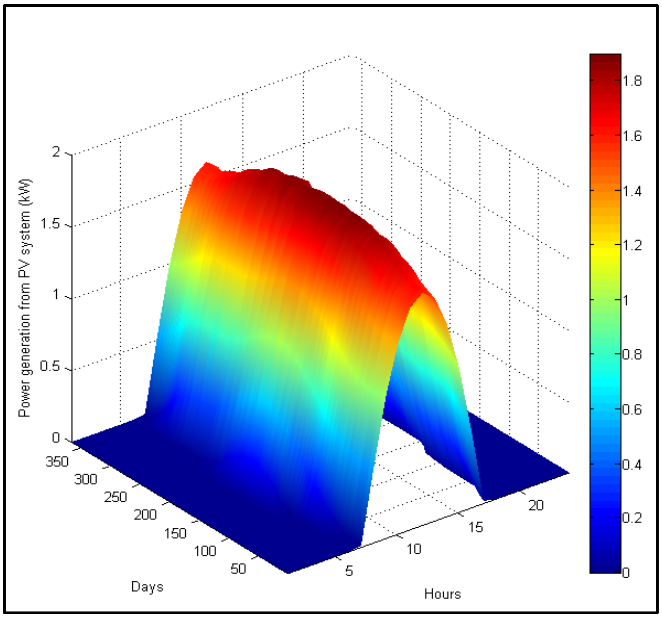

Figure 11. Solar generation for each day in Najaf city with optimally tilt angle for system 2kWp.

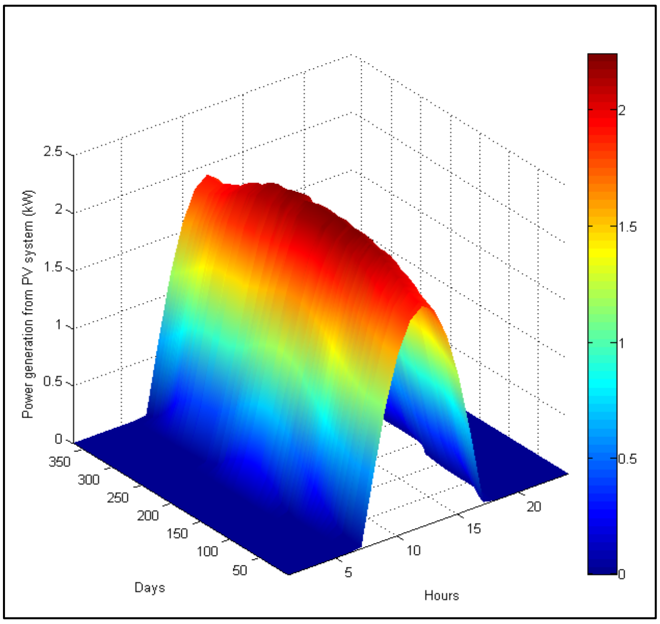

Figure 12. Solar generation for each day in Najaf city with optimally tilt angle for system 2.5kWp.

7. Impact of Solar Generation on Load Demand

In this work, the impact of solar generation for the proposed PV systems will be presented. The effect of solar PV generation with sizes of 1.5kWp, 2kWp, and 2.5kWp, respectively, for Najaf city in January can be seen in Figure 13. Also, the impact of solar generation for the different sizes in June is shown in Figure 14.

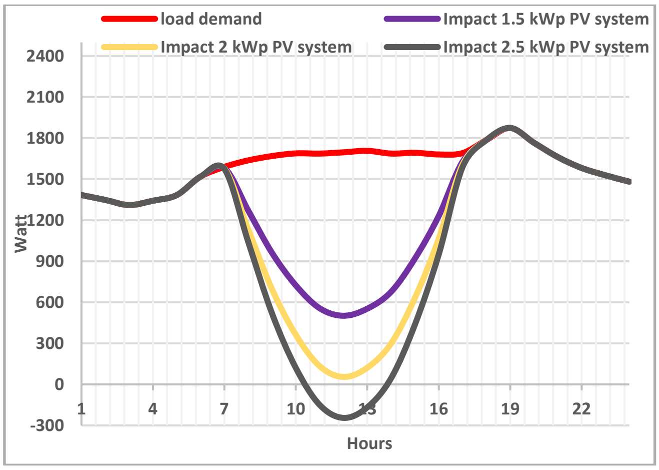

Figure 13. Impact of solar generation in January for different system sizes.

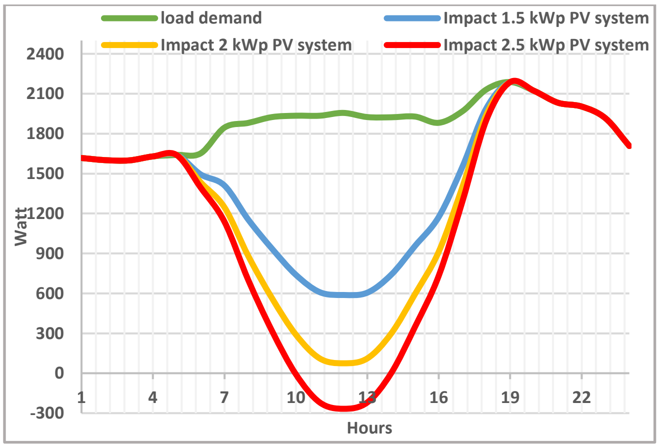

Figure 14. Impact of solar generation in June for different system sizes.

The annual average demand saving of energy consumption for each suggested PV system is 22%, 31%, and 36% with respect to 1.5kWp, 2kWp, and 2.5kWp for each residential consumer in Najaf city. Also, the monthly demand saving of using the mentioned PV systems is shown in Figure 15. It is obvious that there are high percentages in demand savings for months in (March and April) because of the reduction in load consumption for these months. Table (2) illustrates the ranges of demand saving, and each colour indicates a range of percentages. The estimated result for daily demand savings for each month can be seen in Figure 16. It is noted from the demand saving analysis and from the previous figures (13, 14) that there is surplus energy (overgeneration) produced from PV systems at the high period of generation in the noon time. This surplus energy should be utilized by either the application of the load-shifting technique or by saving and storing this energy in batteries.

For large-scale PV systems, the higher penetration of solar PV systems produces a greater decrease in the load demand curve, where the increase in production for the 2 kWp and 2.5 kWp solar systems curves reaches the base load region in the previous figures (13 and 14) of the load curve, and this means completely turning off the traditional electricity power generation plants that operate in the base load area as well as in the intermedium load region in the times during solar energy feeding times. The base load power stations are continuous operation power plants that cannot be turned off because their restart takes two or three days, so increasing the participation of solar power plants to these degrees may be considered relatively incorrect, as illustrated in the figures (13 and 14) the generation of a curve called the duck curve, which is a curve that describes the effect of high PV penetration on the electrical power system and is defined as the actual electrical energy consumed minus solar generation. The main problem in the produced duck curve is that it requires a large amount of electricity to cover the energy required in load demand at sunset times due to the large decrease in solar energy production. So, this increase in energy must, in fact, be provided from traditional sources because it is a large increase in a short time.

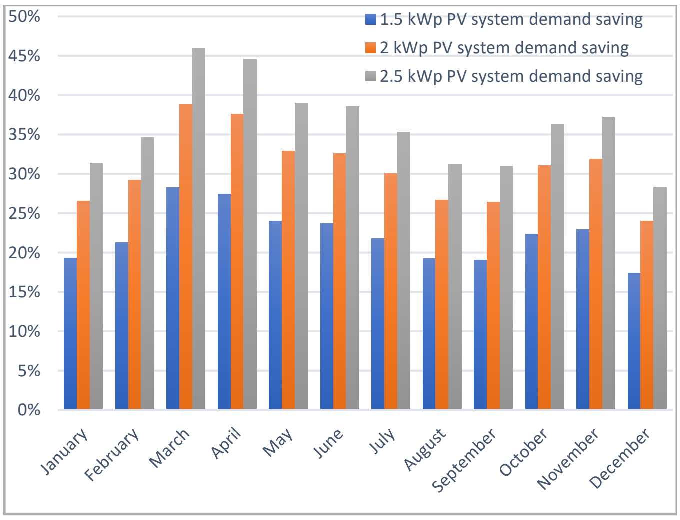

Figure 15. Monthly demand saving for each residential consumer.

Table 2. Ranges of demand saving and their colours.

Range of demand saving Percentage	Colour
(0-3) %	
(3-25) %	
(25-50) %	
(50-75) %	
(75-100) %	
More than 100%	

Under high PV penetration, the electric grid may suffer work stress because the large reverse power may lead to rising of the voltage resulting in reducing the lifetime of the electric grid.so that, there are two significant methods to utilize the overgeneration of solar PV systems:

1. integrating battery storage system with the solar energy system to increase the flexibility of grid work. This technology is deployed to overcome the problem of surplus electricity produced from solar PV systems.
2. applying the load shifting technique in such PV applications with high PV penetration. The load shifting method is used to utilize the surplus energy. It means shifting the loads from low generation periods into high generation periods.

The application of the SG concept can depend essentially on making the consumer control the use of electricity efficiently. So, this basic factor is one of the definitions of active demand side management (ADSM). Furthermore, the tariff structure plays an important role in the application of the SG.

Although the simulation results obtained in this research provide a clear picture of the potential for implementing small-scale solar systems within the smart grid in Najaf, it should be noted that these results have not been verified using direct field measurements. Therefore, it is recommended that future work include collecting operational data from pilot solar projects or homes equipped with similar systems, in order to match the modelling results with actual performance. Benchmarking with international studies or existing local projects in Iraq and the region could also be beneficial, enhancing the credibility of the proposed model and providing a broader database for planning at the national policy level.

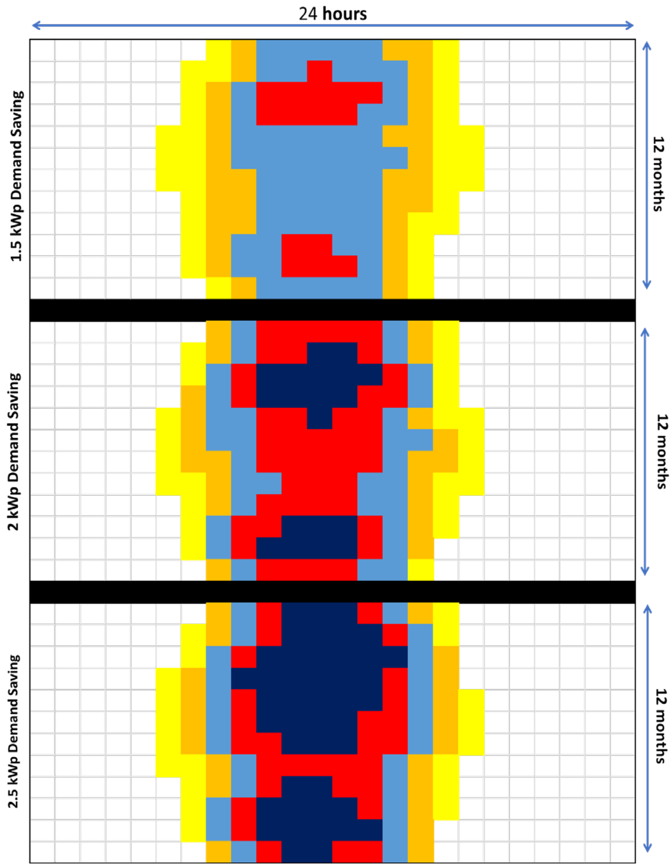

Figure 16. hourly average demand saving for each month with different PV sizes.

8. Potential Policy and Practical Implications

The proposed smart grid model for Najaf city, which integrates rooftop solar generation with optimal tilt angles and system capacities (1.5, 2, and 2.5 kW), has important implications for the national energy strategy and the practices of distribution companies in Iraq. At the policy level, this model could serve as a decision support tool for the Ministry of Electricity to design incentive programs that encourage small-scale distributed generation, such as net-metering systems, incentive tariffs, or tax exemptions for households that adopt solar energy. At the corporate level, implementing this approach could contribute to improving the accuracy of load forecasting, reducing stress on the grid during peak load periods, and enhancing the stability of the electricity system, especially during the summer months when energy demand and solar radiation are at their highest levels. In terms of practical applications, this model can be used in grid planning at the municipal level by identifying priority areas for solar system deployment based on demand patterns and rooftop capabilities. It can also be used in pilot projects to test the operational integration of household solar power systems into the existing grid, providing data to support expansion to other Iraqi cities. Furthermore, the economic modeling of these systems can inform investment frameworks, enabling the public and private sectors to assess the financial viability of distributed generation in urban environments. Thus, this research not only provides technical solutions for demand management, but also establishes a practical framework that can support Iraq's goals of increasing the share of renewable energy and achieving vision 2030 towards a more sustainable and resilient energy system.

This work supports Iraq's energy transition through three main axes:
1. Decentralization: the proposed model relies on small-scale home solar power systems, enabling consumers to become energy producers and reducing reliance on centralized power plants. This decentralization enhances the system's flexibility and enables better load distribution on the grid.
2. Resilience: integrating solar power with the proposed smart grid increases the electrical system's ability to adapt to demand fluctuations and cope with outages or sudden load shedding, especially during peak or emergency periods. It also enables advance planning for various scenarios, reducing the risk of partial or total grid collapse.
3. Low-Carbon Development: relying on solar energy contributes to reducing carbon emissions resulting from reliance on fossil fuels for electricity generation. When implemented on a large scale, this model could significantly contribute to reducing the carbon footprint of the Iraqi electricity sector, in line with global trends and the Sustainable Development Goals (SDGs).

Through these themes, the research reinforces the concept of transitioning to a clean, flexible, and decentralized energy system, and represents a practical step toward achieving a sustainable energy mix in Iraq.

The research results indicate that adopting small-scale solar energy systems with optimal tilt angles can support energy decision-makers on two levels. At the level of planners in distribution companies, these findings help design plans to manage demand and mitigate peak loads, thus enhancing the stability of the electricity grid. At the level of policymakers, these findings provide a scientific basis for developing programs to support and encourage the installation of solar systems, whether through net metering systems or financial incentives for citizens. Therefore, the proposed methodology can serve as a practical tool to guide strategic energy planning in Iraq and contribute to accelerating the transition to a more sustainable electricity system.

9. Economic and Financial Analysis

One of the most essential indicators that demonstrate decision-making value are economic and financial analysis. These include the prices of PV modules, batteries and balance of system. The total cost (C_T) for any solar PV system can be calculated from the given equation [27, 28, 29, 30, 31] with assume that the life cycle is 20 years:

$$C_T = \text{initial cost} + \text{operation and maintenance cost} + \text{replacement cost} \quad (11)$$

The payback period (PBP) can be calculated:

$$\text{PBP} = \frac{C_T}{e \times 350\ days \times size\ of\ system \times 5hours} \quad (12)$$

Where, (e) is the price of electricity unit ($/kWh).
The benefits of the proposed systems if the energy is sell can be estimated:

$$benefits = (e \times 350 \times size \times 5 \times 20) - C_T \quad (13)$$

Table 3 illustrates the economic assumptions of the solar energy based on the prices in the local market in Najaf city.

Table 3. Economic assumptions according to local market prices in Najaf city.

Parameter	Assumption
Price pf solar energy	0.2 $/Wp
Inverter, charge controller and wires	5% of PV array cost
Operation and maintenance	2% of initial cost
Replacement costs	Each 10 years

The obtained results for applying the assumption of the cost analysis for the proposed PV systems can be explained as follows:
1. Table 4 illustrates the cost of implementing 1.5 kWp PV system.

Table 4. Cost of 1.5 kWp PV system.

Parameter	cost
PV array cost	=1500×0.2=300$
Inverter, charge controller and wires	=0.05×300=15$
Initial cost	=300+15=315$
Operation and maintenance	=0.02×315=6.3$/annual
Replacement costs	=15$
Total cost during 20 years	=315+(6.3×20)+15=456$

In case of estimating the payback period and benefits, it is suggested that the unit price of solar energy will be sell in (8 cent/kWh). The payback period can be seen in Figure 17. Also, the benefits will be (3534$) for the suggested unit price of solar energy and the payback period starts at the fourth year. The same procedure can be applied for the other suggested sizes of solar PV systems.

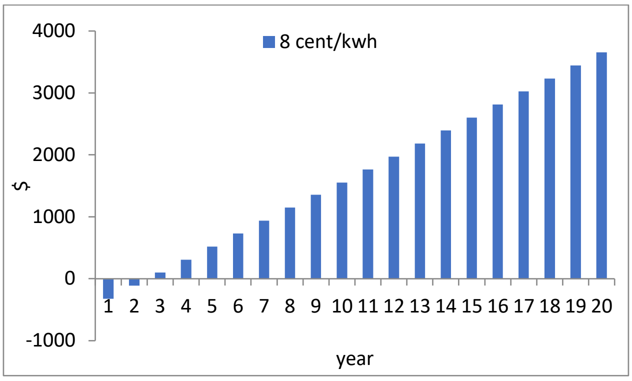

Figure 17. Payback period for 1.5kWp with 8 cent /kWh.

2. Table 5 illustrates the cost of implementing 2 kWp PV system.

Table 5. Cost of 2 kWp PV system.

Parameter	Cost
PV array cost	400$
Inverter, charge controller and wires	20$
Initial cost	420$
Operation and maintenance	8.4$
Replacement costs	20$
Total cost during 20 years	608$

3. Table 6 illustrates the cost of implementing 2.5 kWp PV system.

Table 6. Cost of 2.5 kWp PV system.

Parameter	Cost
PV array cost	500$
Inverter, charge controller and wires	25$
Initial cost	525$
Operation and maintenance	10.5$
Replacement costs	25$
Total cost during 20 years	760$

The implementing of the proposed model in Iraq may face some challenges related to infrastructure and regulation. Current distribution networks are outdated and lack capacity, which may limit the ease of integrating decentralized solar generation into the national grid. The regulatory framework also lacks clear mechanisms such as net metering systems or incentive tariffs, which are essential policies for enabling consumers to participate as energy producers. In addition, maintenance and operational requirements need to be strengthened through training and capacity-building programs for technical personnel.

A gradual roadmap can be proposed in order to support the practical applicability of the suggested PV systems, including the following stages:

1. Accurate field data collection: install small solar radiation and electrical load measurement stations in selected areas of Najaf to verify the accuracy of the simulation.
2. Pilot project: implement a small-scale project on a group of homes (10–20) with 1.5–2.5 kW solar systems and connect them to the grid.
3. Technical evaluation: measure the actual performance of the system in terms of energy production, peak load reduction, and grid stability.
4. Economic evaluation: calculate the economic feasibility for households and electricity utilities, including costs and benefits.
5.Formulate supporting policies: provide recommendations to government agencies regarding incentives, net metering, and supporting legislation.
6. Gradual expansion: following the success of the initial pilots, expand the scope of the application to include additional areas within the city and subsequently to other Iraqi cities.

10. Conclusion

The SG concept, which is the application of DSM based on solar generation, is presented in this work. From the analysis of the electrical load curve for Najaf city in Iraq, it is found that there are two periods with peak load those are: the daytime period, especially in the noontime period, and the night peak load, with (2239) peak hours. So, it is necessary to cover peak load with a flexible electrical system. Three PV systems with sizes 1.5kWp, 2kWp, and 2.5kwp are suggested, and based on the optimization of tilt angle for the proposed case study each month during the year, solar generation is simulated in MATLAB software. The annual demand savings are 22%, 31%, and 36%, respectively, for the suggested PV systems. Also, it is noted that an overgeneration resulting in a load curve is like a duck curve. In large-scale systems, the base load region is affected by high PV penetration, causing a high load demand that requires coverage in short periods. So, the economic factor is important to be studied under high PV penetration.

It is worth noting that the results achieved in this study are not limited to the city of Najaf alone, but also have broader applicability in other Middle Eastern and North African countries with similar climatic conditions. Relying on small-capacity home solar systems with optimized tilt angles contributes to addressing common challenges in the region, such as rapid growth in energy demand, limited transmission and distribution networks, and high carbon emissions. This approach is also in line with prominent regional efforts such as the Shams Dubai program in the UAE, the Noor project in Morocco, Saudi Vision 2030, and solar net metering programs in Egypt. Thus, the methodology proposed in this research can serve as a supportive framework for grid modernization strategies in the region by promoting the gradual integration of decentralized renewable energy into national electricity systems, in line with sustainable development goals and the transition to a low-carbon economy.

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